INTERNATIONAL STANDARD

ISO 24678-4

First edition
2023-06

Fire safety engineering — Requirements governing algebraic formulae —

Part 4: Smoke layers

Ingénierie de la sécurité incendie — Exigences régissant les formules algébriques —

Partie 4: Couches de fumée

Reference number
ISO 24678-4:2023(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

This first edition cancels and replaces ISO 16735:2006, which has been technically revised.

The main changes are as follows:

— the main body has been simplified by making reference to ISO 24678-1;

— the arrival time of smoke front has been introduced in the calculations of smoke filling time in Annex A;

— comparisons with experimental data have been added in Annex A.

A list of all parts in the ISO 24678 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The ISO 24678 series is intended to be used by fire safety practitioners involved with fire safety engineering calculation methods. It is expected that the users of this document are appropriately qualified and competent in the field of fire safety engineering. It is particularly important that users understand the parameters within which particular methodologies may be used.

Algebraic formulae conforming to the requirements of this document are used with other engineering calculation methods during a fire safety design. Such a design is preceded by the establishment of a context, including the fire safety goals and objectives to be met, as well as performance criteria when a trial fire safety design is subjected to specified design fire scenarios. Engineering calculation methods are used to determine if these performance criteria are met by a particular design and if not, how the design needs to be modified.

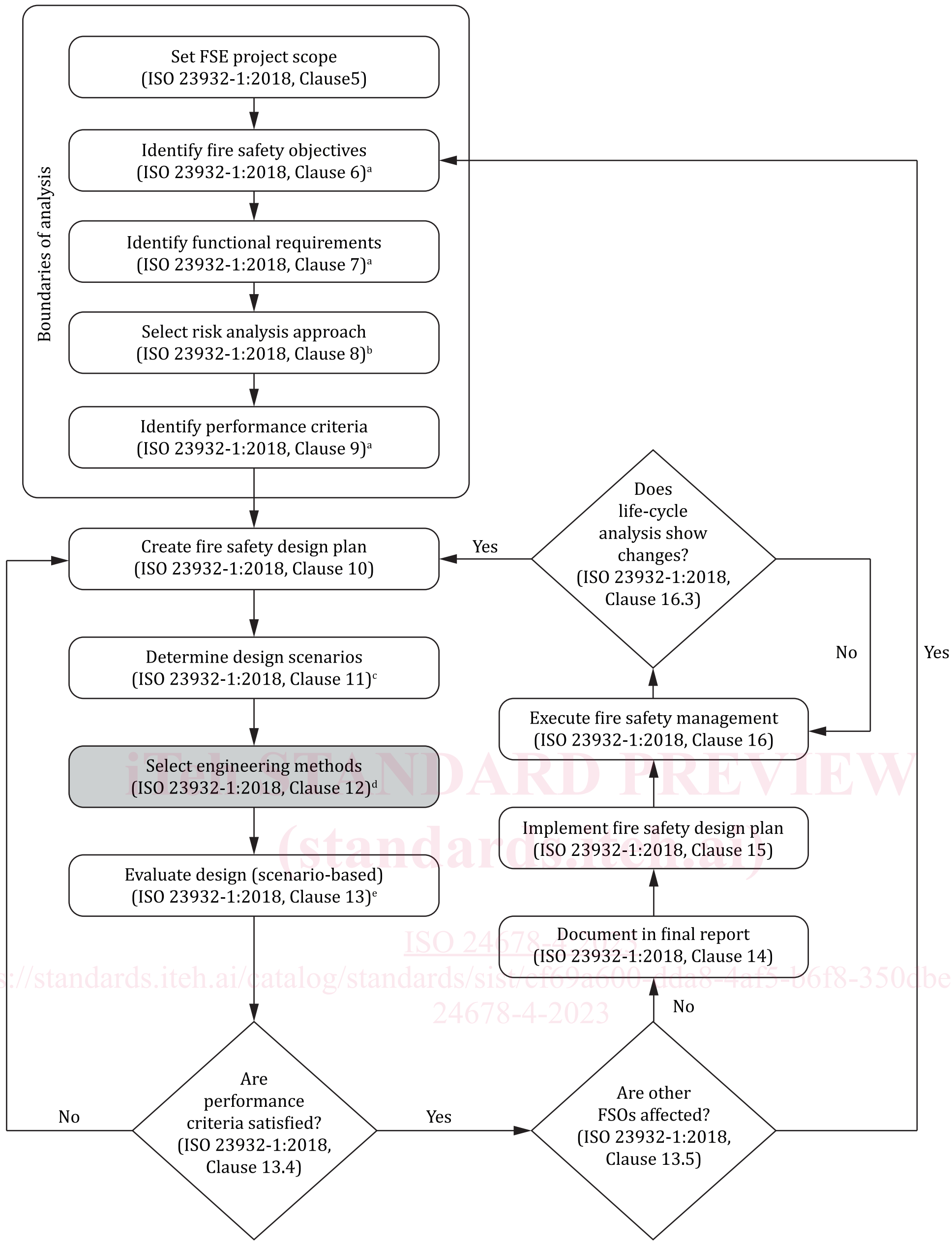
The subjects of engineering calculations include the fire-safe design of entirely new built environments, such as buildings, ships or vehicles, as well as the assessment of the fire safety of existing built environments.

The algebraic formulae discussed in this document can be useful for estimating the consequences of design fire scenarios. Such formulae are valuable for allowing the practitioner to quickly determine how a proposed fire safety design needs to be modified to meet performance criteria and to compare among multiple trial designs. Detailed numerical calculations can be carried out up until the final design documentation. Examples of areas where algebraic formulae have been applicable include determination of convective and radiative heat transfer from fire plumes, prediction of ceiling jet flow properties governing detector response times, calculation of smoke transport through vent openings, and analysis of compartment fire hazards such as smoke filling and flashover. However, the simple models often have stringent limitations and are less likely to include the effects of multiple phenomena occurring simultaneously in the design scenarios.

The general principles of fire safety engineering are described in ISO 23932-1, which provides a performance-based methodology for engineers to assess the level of fire safety for new or existing built environments. Fire safety is evaluated through an engineered approach based on the quantification of the behaviour of fire and based on knowledge of the consequences of such behaviour on life safety, property and the environment. ISO 23932-1 provides the process (i.e. necessary steps) and essential elements for conducting a robust performance-based fire safety design.

ISO 23932-1 is supported by a set of fire safety engineering documents on the methods and data needed for all the steps in a fire safety engineering design as summarized in Figure 1 (taken from ISO 23932-1:2018, Clause 4). This set of documents is referred to as the Global fire safety engineering analysis and information system. This global approach and system of standards provides an awareness of the interrelationships between fire evaluations when using the set of fire safety engineering documents. The set of documents includes ISO/TS 13447, ISO 16730-1, ISO 16732-1, ISO 16733-1, ISO/TS 16733-2, ISO/TR 16738, ISO 24678-1, ISO 24679-1, ISO/TS 29761 and other supporting Technical Reports that provide examples of and guidance on the application of these documents.

Each document supporting the global fire safety engineering analysis and information system includes language in the introduction to tie that document to the steps in the fire safety engineering design process outlined in ISO 23932-1. ISO 23932-1 requires that engineering methods be selected properly to predict the fire consequences of specific scenarios and scenario elements (ISO 23932-1:2018, Clause 12). Pursuant to the requirements of ISO 23932-1, this document provides the requirements governing algebraic formulae for fire safety engineering. This step in the fire safety engineering process is shown as a highlighted box in Figure 1 and described in ISO 23932-1.



a See also ISO/TR 16576 (Examples).

b See also ISO 16732-1, ISO 16733-1, ISO/TS 16733-2, ISO/TS 29761.

c See also ISO 16732-1, ISO 16733-1, ISO/TS 16733-2, ISO/TS 29761.

d See also ISO/TS 13447, ISO 16730-1, ISO/TR 16730-2 to ISO/TR 16730-5 (Examples), ISO/TR 16738, ISO 24678-1, ISO 24678-2, ISO 24678-3, ISO 24678-4 (this document), ISO 24678-5, ISO 24678-6, ISO 24678-7 and ISO 24678-9.

e See also ISO/TR 16738, ISO 16733-1, ISO/TS 16733-2.

NOTE Documents linked to large parts of the fire safety engineering design process: ISO 16732-1, ISO 16733-1, ISO 24678-1, ISO 24679-1, ISO/TS 29761, ISO/TR 16732-2 and ISO/TR 16732-3 (Examples), ISO/TR 24679-2 to ISO/TR 24679-4, ISO/TR 24679-6, ISO/TR 24679-8 (Examples).

Figure 1 — Flow chart illustrating the fire safety engineering (FSE) design process (adapted from ISO 23932-1:2018)

Fire safety engineering — Requirements governing algebraic formulae —

Part 4: Smoke layers

1 Scope

This document specifies the requirements governing the application of a set of explicit algebraic formulae for the calculation of specific characteristics of smoke layers.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13943, *Fire safety — Vocabulary*

ISO 24678-1, *Fire safety engineering — Requirements governing algebraic formulae — Part 1: General requirements*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
boundary
surface that defines the extent of an enclosure

3.2
enclosure
room, space or volume that is bounded by surfaces

3.3
fire plume
upward turbulent fluid motion generated by a source of buoyancy that exists by virtue of combustion and often includes an initial flaming region

3.4
fire source diameter
effective diameter of the fire source, equal to the actual diameter for a circular source or the diameter of a circle having an area equal to the plan area of a non-circular source

3.5
flow coefficient
fraction of effective flow area over total area of a vent

3.6
fuel mass burning rate
mass generation rate of fuel vapours

3.7
heat release rate
rate at which heat is actually being released by a source of combustion (such as the fire source)

3.8
interface position
elevation of the smoke layer interface relative to a reference elevation

Note 1 to entry: It is also referred to as the smoke layer height.

3.9
quasi-steady state
state in which it is assumed that the full effects of heat release rate changes at the fire source are felt everywhere in the flow field immediately

3.10
smoke layer
relatively homogeneous volume of smoke that forms and accumulates beneath the boundary having the highest elevation in an enclosure as a result of a fire

Note 1 to entry: This is also referred to as the hot upper layer and the hot gas layer.

3.11
smoke layer interface
horizontal plane separating the smoke layer from the lower, smoke-free layer

3.12
species yield
mass of a combustion product species generated by the combustion of unit mass of combustibles

3.13
thermal inertia
parameter representing the ability of enclosure materials to absorb heat, calculated by the square root of the product of thermal conductivity, density and specific heat of the material

3.14
vent
opening in an enclosure boundary through which air and smoke can flow as a result of naturally- or mechanically-induced forces

3.15
vent flow
flow of smoke or air through a vent in an enclosure boundary

4 Requirements governing the description of physical phenomena

4.1 The requirements governing the description of physical phenomena as specified in ISO 24678-1 apply, in addition to the requirements specified in the following subclauses.

4.2 The buoyant smoke layer resulting from a fire source in an enclosure is a complex thermo-physical phenomenon that can be highly transient or nearly steady state. In addition to buoyancy, smoke layers can be influenced by dynamic forces due to wind and mechanical fans.

4.3 Smoke layer characteristics to be calculated and their useful ranges shall be clearly identified, including those characteristics inferred by association with calculated quantities (e.g. the association of smoke mass fraction with excess gas temperature based on the analogy between energy and mass conservation) and those associated with heat exposure to objects and occupants by the smoke layer, if applicable.

5 Requirements governing the calculation process

The requirements specified in ISO 24678-1 governing the calculation process apply.

6 Requirements governing limitations

The requirements specified in ISO 24678-1 governing limitations apply.

7 Requirements governing input parameters

The requirements specified in ISO 24678-1 governing input parameters apply.

8 Requirements governing the domain of applicability

The requirements specified in ISO 24678-1 governing the domain of applicability apply.

9 Example of documentation

An example of documentation meeting the requirements in Clauses 4 to 8 is given in Annex A.

Annex A
(informative)

Formulae for smoke layers in an enclosure

A.1 Scope

This annex is intended to describe the methods that can be used to calculate interface position, average temperatures and average mass fractions of specific chemical species of smoke layers that form beneath boundaries during a fire in an enclosure. These calculation methods are based on the principles of mass, species and energy conservations as applied to the smoke layer as a thermodynamic control volume. In this annex, four different sets of formulae are provided. One is for the smoke filling process in a single enclosure during the initial stage of fire. The other three sets are for steady state smoke control by mechanical exhaust or by natural vents.

A.2 Symbols and abbreviated terms used in this annex

A	floor area of enclosure (m^2)
A_{side}	area of a side vent (m^2)
A_{top}	area of a ceiling vent (m^2)
A_{wall}	surface area of enclosure boundary in contact with smoke layer (m^2)
B	width of a side vent (m)
c	specific heat of enclosure boundary material (kJ/kg·K)
c_p	specific heat of air at constant pressure (=1,0) (kJ/kg·K)
C_D	flow coefficient
D_{wall}	thickness of enclosure boundary material (m)
D	fire source diameter (m)
g	acceleration due to gravity (m/s^2)
h_{wall}	effective heat transfer coefficient of enclosure boundary ($kW/m^2 \cdot K$)
H	height of enclosure (m)
H_l	height of lower bound of a side vent (m)
H_U	height of upper bound of a side vent (m)
k	thermal conductivity of enclosure boundary material (kW/m·K)
$\sqrt{k\rho c}$	thermal inertia of enclosure boundary material ($kW \cdot s^{1/2}/m^2 \cdot K$)
L	mean flame height (m)
$\dot{m}_a$	mass flow rate of air coming into an enclosure (kg/s)

$\dot{m}_e$	mass flow rate of smoke exhaust (kg/s)
$\dot{m}_{error}$	error in mass flow rate (kg/s)
$\dot{m}_p$	mass flow rate of gases in fire plume (kg/s)
$\dot{Q}$	heat release rate of a fire source (kW)
$\dot{Q}_0$	heat release rate of a steady fire source (kW)
t	time (s)
t_{ar}	arrival time of plume front at ceiling (s)
t_c	characteristic time for heat absorption by enclosure boundary (s)
T_0	reference temperature, often taken by outside temperature (K)
T_s	smoke layer temperature (K)
$\dot{V}_e$	volumetric flow rate of mechanical exhaust system (m^3/s)
Y	mass fraction of specific chemical species (kg/kg)
Y_0	mass fraction of specific chemical species at reference state (kg/kg)
z	interface position above base of fire source (m)
α	fire growth rate of time-squared growing fires (kW/s^2)
β	fire growth rate of linearly growing fires (kW/s)
ΔH_c	heat of combustion (kJ/kg)
Δp	pressure difference (Pa)
η	species yield (kg/kg)
λ	fraction of heat absorbed by enclosure boundary during smoke filling period
ρ_0	gas density of air at reference temperature (kg/m^3)
ρ_s	gas density of smoke (kg/m^3)
ρ	density of enclosure boundary material (kg/m^3)

A.3 Description of physical phenomena addressed by the formula set

A.3.1 General descriptions of calculation method

A.3.1.1 Calculation procedure

Estimating the smoke layer properties involves the following steps:

— determination of characteristics of the fire source (burning area, fuel mass burning rate, etc.);

— calculation of the height of the smoke layer interface;

— calculation of the temperature and mass fraction of chemical species in the smoke layer.

A.3.1.2 Smoke layer properties to be calculated

The formula set provides interface position, average gas temperature and mass fractions of chemical species. Uniform temperature and mass fractions are assumed over the entire smoke layer volume.

A.3.2 Scenario elements to which the formula set is applicable

The formula set is applicable to smoke layers above a fire source in a quiescent environment. If flow-disturbance by non-fire related phenomena is significant, the formula set is not applicable. For example, the effect of airflow caused by heating, ventilation and air conditioning (HVAC) systems or by external wind should be considered if they have a significant effect. If active fire suppression systems, such as sprinklers, interact significantly with the smoke layer, the formula set is not applicable.

The fire source needs to be small enough so that the mean flame height is lower than the interface position and the characteristic plume width is less than the width of the enclosure (subject to additional restrictions imposed by the formulae used to obtain plume characteristics).

Methods to calculate smoke layer properties are developed for two limit stages. One limit stage is a simple enclosure smoke filling process during the initial stage of the fire when the smoke control system is not yet in operation. The other limit stage is a quasi-steady vented condition when the smoke production rate equals the rate of outflow from the smoke layer. An intermediate stage (i.e. smoke filling is still occurring even though a smoke venting system is in operation) is not treated in this Annex.

A.3.3 Self-consistency of the formula set

The formula set provided in this annex has been derived and reviewed by many researchers (see Clause A.5) to ensure that calculation results from different formulae in the set are consistent (i.e. do not produce conflicts).

A.3.4 International Standards and other documents where the formula set is used

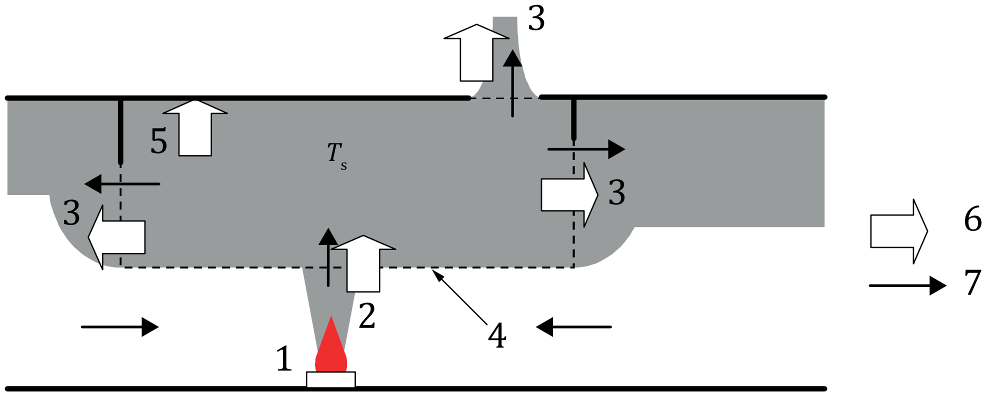
None specified.

A.4 Formula-set documentation of calculation procedure

A.4.1 General description of calculation methods

A.4.1.1 Basic assumptions

As shown in Figure A.1, a smoke layer is generated over a fire source in an enclosure. Smoke is accumulated in the upper part of an enclosure as a result of burning. It is assumed that smoke forms a layer of fairly uniform temperature and species mass fraction. Based on the principles of mass, species and energy conservations applied to the smoke layer, average values of temperature, species mass fraction and interface position are calculated.[27],[28],[29] Descriptions of fire plumes and vent flows are given in ISO 24678-2 and ISO 24678-5, respectively.



Key

1 fire source
2 plume flow
3 vent flow
4 smoke layer (control volume)
5 heat absorption by enclosure boundary
6 heat flow
7 mass flow

Figure A.1 — General heat and mass conservation of smoke layer in an enclosure with a fire source

A.4.1.2 Mass conservation

Conservation of mass in the smoke layer is considered over an appropriately chosen control volume as shown in Figure A.1 by broken lines. The mass flow rate incoming across each interface (negative for outgoing flow) of the control volume is equal to the rate of mass accumulation in the smoke layer. Plume flow, vent flows and other flows are considered where necessary.

A.4.1.3 Energy conservation

Conservation of energy in the smoke layer is considered in a similar way to mass conservation. The energy flow rate incoming across each interface (negative for outgoing flow) of the control volume is equal to the rate of energy accumulation in the smoke layer. In addition to plume and vent flows, radiation losses and heat absorption by the enclosure boundary are considered appropriately.

NOTE When it is difficult to determine the radiation heat loss from the flame, the energy flow rate from the fire plume can be approximated by the total heat release rate.

A.4.1.4 Conservation of specific chemical species

Mass conservation of specific chemical species is considered in a similar way to total mass conservation. In addition, if the gas phase chemical reaction can take place in the smoke layer, the reaction rate can be considered appropriately.

A.4.1.5 Mass flow rate of fire plume through interface position

The mass flow rate of the fire plume at the interface position (bottom surface of smoke layer) is given as a function of the heat release rate of the fire and the vertical distance between the base of the fire source and the interface position. An example of a set of explicit formulae for mass flow rate is given in ISO 24678-2.